Recoil-distance lifetime measurement in 37Cl

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RECOIL-DISTANCE LIFETIME MEASUREMENT IN ^{37}Cl

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Résumé. — Des vies moyennes de (19,6 ± 3,0) ps et (32,8 ± 2,0) ps pour les états $7/2^-$ à 3 103 keV et $9/2^-$ à 4 011 keV dans ^{37}Cl ont été mesurées par la méthode du parcours de recul dans la réaction ^{27}Al(^{12}C, 2p)^{37}Cl. Parmi les transitions M2 connues dans les noyaux de la couche 2s-1d, celle issue du niveau à 3 103 keV dans ^{37}Cl apparaît comme étant la plus intense. Une mesure de déplacement Doppler atténué a permis d'évaluer une limite supérieure de 0,8 ps pour le temps de peuplement dans la réaction de fusion-évaporation ^{27}Al(^{12}C, pn)^{37}Ar.

Abstract. — Using the recoil-distance technique in the ^{27}Al(^{12}C, 2p)^{37}Cl reaction, mean lives of (19.6 ± 3.0) ps for the $7/2^-$, 3 103-keV state and (32.8 ± 2.0) ps for the $9/2^-$, 4 011-keV state in ^{37}Cl have been measured. The strength of the M2 decay from the 3 103 keV level appears to be the strongest among known M2 transitions in 2s-1d nuclei. An upper limit of 0.8 ps for the feeding time in the fusion-evaporation reaction ^{27}Al(^{12}C, pn)^{37}Ar was estimated from an attenuated Doppler-shift measurement.

1. **Introduction.** — A search for $J^\pi = 7/2^-$ states in odd mass s-d nuclei and a study of their electromagnetic properties are currently underway in this laboratory [1]. In the cases where spin, lifetime, branching and mixing ratios are well established, it appears that the γ-decays of these states to the $J^\pi = 3/2^+$ ground states proceed via mixed M2-E3 transitions and that the partial M2 lifetimes are always retarded compared to the single-particle estimates [2]. In this paper we report on a recoil-distance method (RDM) measurement of the lifetime of the 3 103 keV state in ^{37}Cl for which only a lower limit of 10 ps was known [3] at the time the present experiment was performed. The $7/2^-$ spin-parity assignment for this state, as well as the branching and mixing ratios for its ground state transition, have been determined in the past [3], so that the lifetime value directly leads to the magnetic quadrupole and electric octupole ground-state transition strengths.

A heavy-ion induced compound-nuclear reaction was chosen for populating the ^{37}Cl states. Such reactions involve large angular momenta transfer resulting in strong population of high-spin states, which are of interest here. Furthermore, such reactions yield large and forward directed velocities for the reaction products. Consequently, only singles γ-ray spectra are needed for the RDM lifetime measurement. The bombardment of ^{27}Al by 31 MeV ^{12}C ions produced the ^{37}Cl states via the 2p exit channel. At that bombarding energy other exit channels were also open and lifetimes for states in ^{34}S, ^{36}Cl and ^{37}Ar were obtained as by-products.

2. **Experimental procedure and analysis.** — A 50 nA beam of ^{12}C ions from the M. P. Tandem Van de Graaff accelerator was used to bombard the aluminium targets. Gamma-rays were detected in a 84 cm^3 Ge(Li) detector. The detector system had an intrinsic resolution of 2.8 keV for 1.33 MeV γ-rays.

A singles spectrum recorded at 31 MeV bombarding energy, where the yield for the 3 103 keV line was found to be maximum, is shown in figure 1. A target evaporated onto a thick lead backing was used and the Ge(Li) counter was placed at an angle of 55° to the beam direction. Most of the numerous lines present in this spectrum could be identified and attributed to transitions in ^{34}S, ^{35}Cl, ^{36}Cl, ^{37}Cl and ^{37}Ar.

2.1 RECOIL-DISTANCE LIFETIME MEASUREMENTS. — The experimental set-up for the lifetime measurements is identical to that described in ref. [4]. A 100 μg/cm^2 self supporting stretched target was used. A 7 mg/cm^2 gold foil, sufficient to stop the recoil ions, was stretched in the same manner as the target and used for the stopper. The beam was stopped in a thick tantalum foil mounted behind the stopper foil. The γ-rays were observed for various plunger distances with the Ge(Li) detector placed 7 cm from the target and at 0° to the beam direction.

The average axial velocity of the recoiling ions

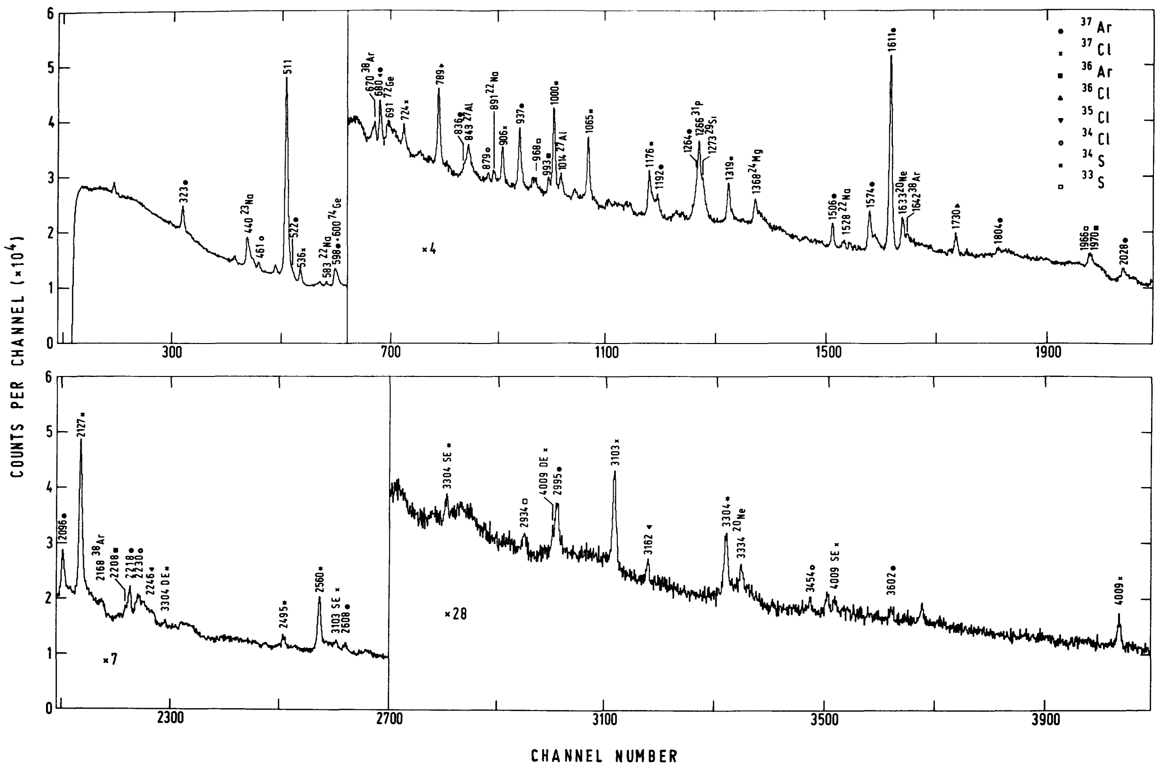

FIG. 1. — Gamma-ray spectrum recorded at 55° with respect to the beam axis for the ^{27}Al + ^{12}C reaction at a bombarding energy of 31 MeV.

was determined from the energy differences between the stopped E_0 and shifted E_s peaks. The corresponding areas, I_0 and I_s, were obtained with a least-squares fitting program using Gaussian line shapes superimposed on a background fitted to a polynomial series. The experimental ratios $R = I_0/(I_0 + I_s)$ of the unshifted peak area to the total area, were then calculated at each plunger distance. For cases where the shifted peaks were obscured by contaminants in the γ-spectra, the intensities I_0 were normalized to the intensity of the stopped peak of the 1 611 keV γ-rays deexciting the long-lived ^{37}Ar 1 611 keV state, corrected for its own decay with a lifetime $\tau = 6.38 \pm 0.15$ ns [5].

The lifetime values were obtained by comparing the experimental values of the ratio R to the values calculated for a level which is fed both directly from the reaction and by γ-ray cascades from higher lying levels. In this calculation the small direct feeding-time (see Section 3.3) was neglected.

The direct and cascade population fractions were taken from the γ-ray spectrum recorded at 55°. Corrections due to γ-ray detection efficiency and to the motion of the recoiling nuclei were found to be negligible compared to the statistical errors.

2.2 DOPPLER SHIFT ATTENUATION MEASUREMENT. — By bombarding the target evaporated on the thick lead backing, γ-ray singles spectra were measured at the angles of 0°, 55° and 90°. From there a value for the attenuation factor $F = 0.29 \pm 0.04$ was deduced for the 598 keV γ-ray transition decaying the 7 071 keV level in ^{37}Ar. The error on the attenuation factor arises mainly from the presence of the 600 keV γ-ray line produced by neutron inelastic scattering on ^{74}Ge.

3. **Results.** — The values of the mean-lives obtained in the present work are listed in table I where they are compared to previous measurements.

3.1 THE 5 689 keV LEVEL IN ^{34}S. — Using a mean recoil velocity of 1.91 % the lifetime value for the 5 689 keV level was determined by analysing three γ-ray transitions, namely the 5 689 → 4 622 keV, the 4 688 → 2 127 keV and the 3 304 → 0 keV transitions. This could be done because the lifetime of the lower states are much shorter than 1 ps [3]. Since the shifted peak for the 1 067 keV γ-ray transition was much

TABLE I

Summary of recoil distance lifetime measurements

Nucleus	Level (keV)	τ (ps) present	τ (ps) others	Ref.
^{34}S	5 689	52.9 ± 2.4	54 ± 5	[6]
^{36}Cl	789	32.3 ± 2.5	3.0 ± 0.8	[3]
			> 5	[7]
			30 ± 1	[8]
^{37}Cl	3 103	19.6 ± 3.0	16 ± 9 (¹)	[9]
			48 ± 5	[10]
	4 011	32.8 ± 2.0	31 ± 3	[10]
^{37}Ar	6 473	9 ± 2	6.3 ± 0.6	[11]

(¹) Direct timing measurement using a pulsed beam.

broader than the stopped peak the lifetime value was also calculated using the line shape of the shifted peak in the manner described by McDonald *et al.* [12]. The two values differed by 2.4 %. The analysis of the three transitions using a mean value for the recoil velocity yield an average value of $\tau = 52.9 \pm 2.4$ ps, where the error takes into account the difference obtained for the two different treatments of the 1 067-keV γ-decay curve. This value is in excellent agreement with the value obtained by the RDM in the ^{31}P(α, pγ) reaction [6].

3.2 THE 789 keV LEVEL IN ^{36}Cl. — Two strong γ-rays from the decay of ^{36}Cl levels were observed in the spectra taken at 55°, namely the 1 730 keV and 789 keV γ-ray transitions from the 2 519 → 789 → 0 keV cascade.
Whereas a single value of 2.36 ± 0.16 ns is reported for the lifetime of the 2 519 keV level, the two values reported for the lifetime of the 789 keV level differ by a factor of ten [3]. In the present χ^2 analysis of the 789 keV level decay curve a best value of 45 % is obtained for the population fraction of this level through the 2 519 keV level, whereas a value of 59 % is deduced from the photopeak intensities in the 55° spectrum taken at 31 MeV. This indicates that another 1 730 keV line, which could not be identified, is underlying the 2 519 → 789 keV γ-ray transition. This is corroborated by the normalized 1 730 keV stopped peak versus stopper distance curve which does not display a simple exponential decay. So by using the value of 45 % for the cascade population and the value of $\tau(2\,519) = 2.36 \pm 0.16$ ns, a value of 32.3 ± 2.5 ps is obtained for the lifetime of the 789 keV level.

3.3 THE 7 071 keV LEVEL IN ^{37}Ar. — A lifetime value of $\tau_1 = 0.55 \pm 0.12$ ps has been determined for this level in the ^{34}S(α, nγ) reaction [11]. In the present ^{27}Al(^{12}C, pnγ)^{37}Ar reaction no known higher lying levels could be identified and therefore the measured attenuation factor in the DSA measurement may be due to the lifetime of the 7 071 keV level and to the feeding time τ_f, i.e. the time interval between the reaction and the population of this state. A value of 0.34 ± 0.20 ps for the feeding time may be deduced from the attenuation factor F using the two-component decay chain formula

$$F = (\tau_f F_f - \tau_1 F_1)/(\tau_f - \tau_1) .$$

By using this formula, one assumes that the feeding of the 7 071 keV level may be approximated by an exponential decay. Furthermore, it should be remembered that large uncertainties remain in lifetime determination by the DSA method. Therefore only an upper limit of $\tau_f < 0.8$ ps may be given from the present analysis.

3.4 THE 6 473 keV LEVEL IN ^{37}Ar. — Lifetime values for this level have been determined using both the total area of the 323 keV γ-ray transition and the external normalisation. No difference within the statistical errors was observed between both values.

3.5 THE 3 103 keV AND 4 011 keV LEVELS IN ^{37}Cl. — Both the 4 011 → 3 103 keV and 4 011 → 0 keV γ-ray transitions have been analysed (see Fig' 2) and yield a mean value of 32.8 ± 2.0 ps for the lifetime of the 4 011 keV level. This value has been used in the analysis of the decay of the 3 103 keV level, since 60 % of the feeding of this latter was found to proceed via the 4 011 keV state. The present lifetime value, $\tau = 19.6 \pm 3.0$ ps, is in strong disagreement with a recent RDM result in the ^{34}S(α, pγ) reaction [10], but supports a less precise value obtained by direct timing using a pulsed beam [9].

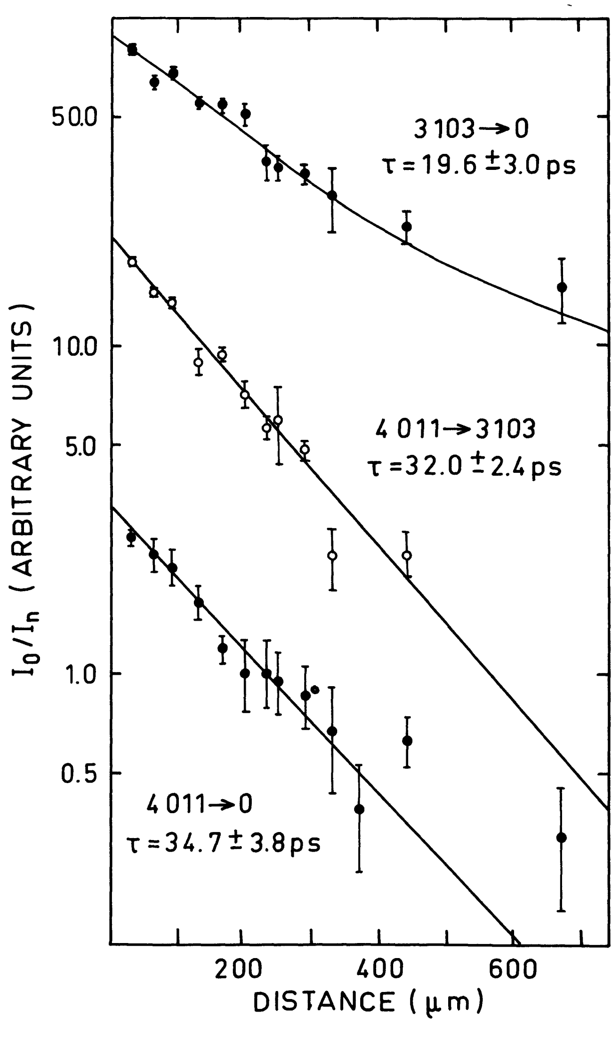

FIG. 2. — Intensity ratios as a function of stopper distance for three transitions in ^{37}Cl. The normalising factor I_n is the area of the stopped peak for the 1 611 → 0 transition in ^{37}Ar, corrected for its decay.

4. **Discussion.** — Transition strengths in ^{37}Cl deduced from the present lifetime measurements are reported in table II.

The strength of the M2 decay from the 3 103 keV

TABLE II

Transitions strengths in ^{37}Cl

$J_i^\pi \to J_f^\pi$	Transition strength (W.u.) ([1]) E2	E3	M1	M2
$7/2^- \to 3/2^+$		12.4 ± 2.4		0.69 ± 0.11
$9/2^- \to 3/2^+$		12.2 ± 0.8		
$9/2^- \to 7/2^-$	1.3 ± 0.1		$(5.9 \pm 0.4) \times 10^{-4}$	

([1]) Branching and mixing ratios are from ref. [10].

level appears to be the strongest among the known M2 transitions in 2s-1d nuclei. In fact the transition rate is close to the single-particle estimate. Several shell model descriptions for the first $7/2^-$ state have been used to predict the transition rate and the deduced values range from 0.3 to 5 W.u. [13]. The great majority of M2 transitions in nuclei with $A > 30$ is severely inhibited and this inhibition has been discussed by Kurath and Lawson [14]. They showed in particular that M2 transitions in the $d_{3/2}$-$f_{7/2}$ region will be inhibited in the frame of the strong-coupling model. In this model the intrinsic excited state is formed by raising a particle from one of the orbitals k_d originating from the $d_{3/2}$ shell to an orbital k_f originating from the $f_{7/2}$ shell. Kurath and Lawson computed the values of the hindrance factor for the $7/2^- \to 3/2^+$ M2 transitions according to the different (k_d, k_f) sets involved. The smallest factor (~ 2) was found for $k_d = 3/2$ and $k_f = 7/2$, and these are indeed the Nilsson orbitals which would be involved in the M2 transition of ^{37}Cl if this nucleus had an oblate deformation.

Large and identical strengths for the E3 transitions arising from the 3 103 and 4 011 keV levels are observed. This may reflect the presence of a 3^- core excitation in the wave functions of the $7/2^-$ and $9/2^-$ states.

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